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Procedia CIRP 26 (2015) 355 – 360

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12th Global Conference on Sustainable Manufacturing

Energy saving potentials of high pressure lubricoolant supply

Fritz Klocke[a], Benjamin Döbbeler[a]*, Dieter Lung[a]

[a] Laboratory for machine tool and production engineering (WZL) of RWTH Aachen University, 52074 Aachen, Germany

* Corresponding author. Tel.: +49 241 80 28251; fax: +49 241 80 22293. *E-mail address:* b.doebbeler@wzl.rwth-aachen.de

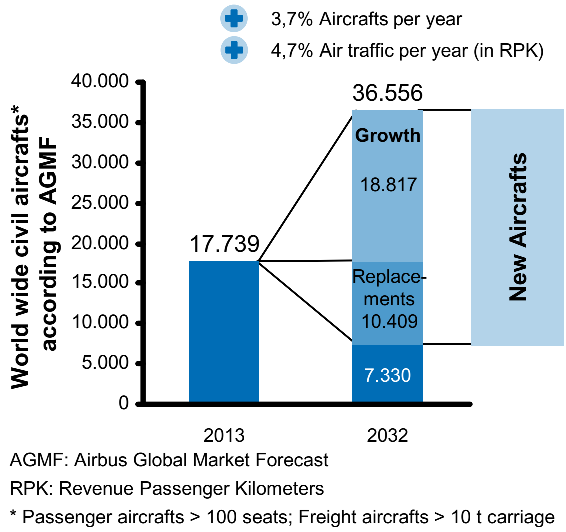
Abstract

During recent years high pressure lubricoolant supply in cutting technologies has been emerging, especially for difficult to cut materials in the aerospace industry, for example Inconel 718 or titanium alloys. The potentials are highly promising with respect to reduced flank wear, lowered process temperatures and thus higher achievable productivity rates. This paper aims to highlight possibilities of the technology whilst focusing on energy efficiency matters. The area of conflict between high pressure, thus high power electrical power demand as well as higher productivity rates, and low pressure, thus high energy efficiency, will be discussed in detail and propositions will be made. It will be shown that processes exists in which high pressure lubricoolant supply is highly productive and even ecologically beneficial, despite of the additional power consumption caused by high pressure pumping aggregates.

Keywords: High pressure lubricoolant supply, machining, resource efficiency

1. Introduction

During the last years, a lot of work on high pressure lubricoolant supply has been performed at different research institutes as well as in the industrial application. Mostly the efforts concern the aerospace industry regarding difficult to cut materials due to the high potential productivity and stability increase of the process. Especially in the turbine manufacturing high-temperature resistant materials such as nickel based alloys, e.g. Inconel, or titanium based alloys are used. As shown in Fig. 1 the number of aircrafts is highly increasing over the next 20 years according to the Airbus Global Market Forecast [1]. Regarding the increase of aircrafts (3,7% p.a.) resulting from the growth of air traffic per year (4,7% p.a.), in 2032 more than 35.000 aircrafts are estimated to be in service. Of these, 18.000 are necessary due to growth, whereas 10.000 will be replacement of actual airplanes, leading to 28.000 new aircrafts which need to be build. This leads to an significantly increasing necessity of manufacturing high-temperature resistant materials used in the turbo-machinery. Furthermore, the machinability of these materials used in engines progressively arises challenges for cutting technologies and production engineering.



doi:10.1016/j.procir.2014.07.123

Fig. 1: Estimation of aircraft growth up to 2032 (according to the AGMF [1])

The high pressure jet assisted lubricoolant supply is one possibility in cutting operations to increase productivity, tool wear and quality of the process in general. High pressure lubricoolant supply does not only consist of high pressure pumps and increased volume flows in comparison to conventional lubricoolant supply. Furthermore the utilization of one or several nozzles near the cutting zone mounted on the tool holder itself is one of the key benefactors enhancing the lubricoolant supply, namely jet assisted lubricoolant supply. Another key factor is the orientation of the jet on the rake face of the cutting tool, compare Fig. 2.

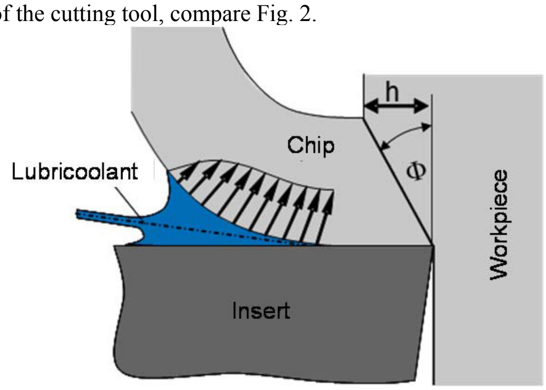


Fig. 2: High pressure jet assisted lubricoolant supply

As can be seen in the figure above, the lubricoolant jet supply results in a deep penetration of the zone between the chip and the rake face of the tool.

High pressure is a relative term and is used differently. In the literature, occasionally high pressure lubricoolant supply with more than 1000 bar is used for cutting operations, but with limited volume flows up to 5 l/min. On the other hand, pressures up to 400 bar are used with either high pressure and low volume flow or vice versa [2, 3]. In this paper high pressure is considered up to 350 bar. At the WZL a ChipBLASTER CV16-5000 is available. This aggregate combines filtration, a tank as well as the supply pump in one portable aggregate. Furthermore it is able to provide a pressure of 350 bar with volume flows up to 60 l/min. But a pressure of 350 bar might not lead to an economical advantageous process design. Especially regarding the energy and resource efficiency, lower pressures or at least a sound combination of pressure and volume flow enabling a higher productivity rate are preferable. Notably, the additional expenses for the high pressure pumps, fine filtration, special tools and tool holders as well as possible machine components such as seals and an increased suction require an substantial increase in productivity in order to assure profitability. For example high pressure supply leads to higher dispersion of the lubricoolant jet. Therefore sealings of the machine need to be more elaborate and even a more powerful suction including effective oil separation might be necessary. Also the chips gain higher velocities inside the machine tool. Due to this higher speed transparent materials such as windows which are not resistant enough get opaque and need to be changed.

2. Potential of high pressure lubricoolant supply in machining

The potentials of high pressure jet assisted lubricoolant supply will be addressed in this chapter. The basic effects of the high pressure lubricoolant supply result in the increased cooling of the cutting area and a deeper penetration of the cutting fluid between the bottom of the chip and the rake face of the tool. Another effect is the reduction of friction in comparison to conventional cooling techniques. This cooling effect promotes chip breakage as well as the reduction of tool wear. Whereas the tool wear reduction is a consequence of the increased cooling, the chip breakage also benefits from the higher mechanical force of the lubricoolant jet on the one hand and from the increased cooling and thus reduced strength of the material due to lower temperatures on the other hand [3]. Often longer chips, commonly occurring in grooving operations, may harm the machine tool operator or prohibit automatic process sequences. The jet assisted lubricoolant supply with higher pressures depending on the workpiece material, often provides shorter chips. In several research cases, the control of the chip breakage could only be achieved by combining special rake face geometries and high pressure lubricoolant supply.

Earlier results show, that the temperatures near the cutting zone, measured with a two color pyrometer, can be decreased by 200 °C compared with conventional flood cooling in grooving operations performed on a lathe. This effect has been proven for different materials, such as Ti6246 and X5CrNi18-10. Unfortunately, these high temperature reductions are only possible when applying high pressure (> 250 bar) which often leads to a economically disadvantageous process. Furthermore the effect of the pressure was more significant than the effect of the volume flow, meaning that an increase of the pressure leads to more significant temperature reductions than an increase of volume flow [3, 4]. Untouched from this findings is, that in increase of volume flow undoubtedly has a positive effect on temperature reductions near the cutting zone. In contrary, this effect will stops as soon as the width of the jet reaches the chip width. At this point a further increase of the volume flow, which leads to a wider jet, has no positive effect as it does not impinges on the chip. At this point further enhancement can only be achieved by elevating the pressure [3].

Beyond these potentials there is still research necessary to further explain the ongoing mechanisms in the cutting zone and during wear development. This is underlined by investigations, where an additional supply of lubricoolant from the flank face led to a shorter tool life time [3].

3. Resource efficiency of high pressure lubricoolant supply strategies

Studies show that the power consumption of the manufacturing processes on machine tools basically depend on the consumed electrical energy and the material of the workpiece itself [5]. Within the consumption of electrical energy, especially the lubricoolant supply accounts for a significant ratio of the total consumption. Studies show that up to 30 % of the total energy consumption for manufacturing sample workpieces are caused by lubricoolant pumps, filter pumps as well as chilling devices for lubricoolant temperature control [6, 7].

For the high pressure lubricoolant supply, the ChipBLASTER CV16-5000 high pressure aggregate has been measured at the WZL. This aggregate is able to supply lubricoolant with a pressure up to 350 bar with a volume flow up to 60 l/min. The electrical power consumption has been measured with a Chauvin Arnoux 8335 power quality analyzer, which allows to measure with sample frequencies of 6.4 kHz – 25.6 kHz for 50Hz grids [8]. During this investigation the electrical power consumption of the pump has been analyzed depending on the pressure and flow rate. By using changeable nozzles with varying outlet diameters at the tool holder, different volume flow rates corresponding to adjusted pressure levels could be set up. The external lubricoolant supply aggregate can be used on virtually every cutting process and has been investigated on a CNC-lathe for grooving operations, since high pressure lubricoolant supply has a significant effect on this kind of process. In the following Fig. 3 the electrical power consumption of the lubricoolant supply aggregate is shown.

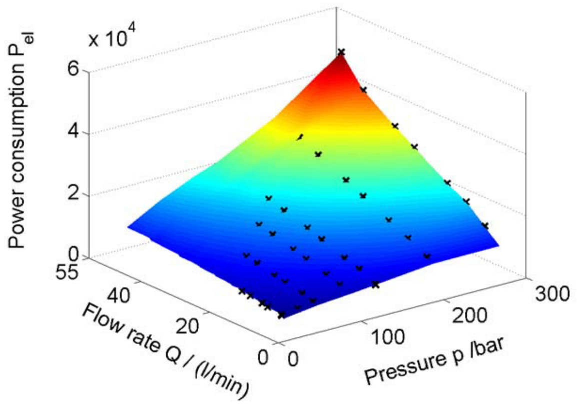


Fig. 3: Electrical power consumption depending on flow rate and pressure

In this 3D-plot, the electrical power consumption follows the underlying fluid mechanical principles. The power consumption in a simple way can be described as

$$P_{el} = \eta \cdot p \cdot Q$$

where η accounts for the pump efficiency of providing pressure and volume flow from electrical energy. Further the exit speed of the lubricoolant v_{nozzle} is directly linked to the pressure. In a simplified approach derived from the Bernoulli equation it can be approximated as

$$v_{nozzle} = \sqrt{2 \cdot \frac{(p_{total} - p_{stat})}{\rho}}$$

with p_{total} as total pressure of static, dynamic and hydrostatic pressure, p_{stat} as static pressure and ρ as density of the lubricoolant. This leads to a volume flow of

$$Q = v_{nozzle} \cdot A$$

The outlet cross section A depends on the nozzle diameter. With these equations the dependence of the electrical power consumption of the pressure is exponentially, $P_{el} \sim \eta \cdot p^x$, where $x > 1$. Consequently, higher pressures result in significantly higher electrical power consumption of lubricoolant supply pumps [3].

Often in the industry, lubricoolant supply pumps operate at their limit, leading to a simple "on or off"-strategy. Even more often, bypass solutions are used to adjust the volume flow or pressure to the cutting zone. A part of the volume flow is just directly transported into the lubricoolant tank by using manually operated valves. In both cases the maximum electrical power consumption is necessary at the pump. One advantage of high pressure aggregates is, that frequency controls of the pumps are common and the needed pressure and volume flow can directly be set up and therefore no unnecessary power consumption due to the supply aggregates is dissipated. The question at hand is, whether the exactly needed pressure and volume flow for different cutting processes can be determined. Furthermore it is necessary to understand the possibilities of high pressure supply in order to estimate the advantageousness [9, 7].

Earlier investigations showed that, from an energetic point of view, high pressure lubricoolant supply is advantageous when applying higher cutting speeds and thus increasing the productivity [4]. The following Table 1 shows the two different settings under investigation and their results at the WZL. On the one hand the internal lubricoolant supply of the CNC-lathe Monforts RNC 400 with about 6 bar has been used. On the other hand the external ChipBLASTER aggregate supplied the lubricoolant. In this case a special high pressure product from has been used (Fuchs Ecocool TN2525HP). In order to show the potential, in the second parameter set the cutting speed has been doubled from 200 m/min to 400 m/min.

One of the key factors, the tool lifetime, has been decreased in the experiments due to higher workload caused by the doubled cutting speed. On the other hand the total removed volume with one tool increases in setting 2 which leads to an advantage in tool life. It is obvious that the average power consumption including the process of the second setting is higher than with lower cutting speeds. This finding correlates with the common understanding of decreasing cutting forces when applying higher cutting speeds [10].

Table 1: Comparison of lubricoolant supply strategies [11]

Parameter	Setting 1	Setting 2
Workpiece material	X5CrNi18-10	
Cutting speed v_c [m/min]	200	400
Feed f [mm]	0.15	0.15
Depth of cut a_p [mm]	2.5	2.5
Lubricoolant supply strategy	Internal	External
Lubricoolant supply pressure p [bar]	6	150
Lubricoolant supply volume flow [l/min]	10	23
Average power consumption of CNC lathe including the process $P_{el,lathe}$ [W]	10 341	9 073
Average power consumption of ChipBLASTER $P_{el,CB}$ [W]	0	3 373
Average total power consumption [W]	10 341	12 446
Tool life criteria VB_{max} [µm]	100	100
Tool lifetime T [min]	9	5.3
Removed material V [cm³]	675	795
Total energy during machining E [MJ]	5.58	3.96
Specific Energy $E_{el,spec}$ [J/cm³]	**13 788**	**8 297**

Furthermore the material removal rate is doubled as well, which leads to a much shorter process time and thus to a decreased average power consumption. This is in line with previous studies regarding the influence of cutting parameters on the electrical power consumption [12]. On the other hand the total average power consumption of setting 2 is higher than for setting 2 due to the external lubricoolant supply and the corresponding power consumption of about 3 kW in this examined example. But again, because of the shorter process time, the total energy consumption is significantly lower when using setting 2 with external high pressure lubricoolant supply. On the contrary, the increase of process time might lead to higher idle times, if the machine is not a bottleneck machine. In this case, batch production and flexible machine tools with standby modes are highly advisable in order to decrease idle time consumptions. In the end, process time reductions are most advantageous when being able to switch the machine tool into low-power-consuming states or avoid idle times.

Regarding the lubricoolant itself, it has to be stated that when using high pressure rates, the lubricoolant has to be adapted in order to withstand the higher loads. In this case the already optimized lubricoolant ecocool TN2525HP by Fuchs Petrolub has been used. During the beginning of high pressure investigations at WZL, the previously used emulsion dispersed almost instantaneously. Further investigations regarding the additional efforts at lubricoolant manufacturing did not take place. Whether deterioration occurs when using higher pressure has not been investigated at a laboratory level, but feedback from close industrial partners using high pressure lubricoolant supply at more than 100 bar in permanent production shows no accelerated deterioration in comparison to conventional lubricoolant applications.

One finding is, that the tool lifetime with a tool life criterion of 100 µm flank wear decreases. On the contrary, the removed material per tool increases due to the higher material removal rate. Therefore, the increase of the cutting speed possible due to the high pressure lubricoolant supply, neither increases tool costs nor energy costs, but significantly accelerates the process.

In this investigation, the energy consumed for producing the cutting tools has not been regarded yet. The knowledge whether this energy has an influence on the total energy consumption of the process has to be highlighted. Previous publications investigated the energy necessary to manufacture cemented carbide cutting inserts [11, 13, 5]. Tools comparable to the tools used during the investigations incorporate a primary energy demand of 4470 kJ [11]. In comparison to the total energy during machining, the share of the tools is ~13% for setting 1 and for setting 18% as highlighted in Fig. 4. In this figure, the primary energy demand for cutting one cm³ of workpiece material is shown. Hence, the functional unit is the grooving of 1 cm³ X5CrNi18-10 on the Monforts RNC 400 CNC lathe using conventional lubricoolant supply (process 1) or external high pressure supply (process 2).

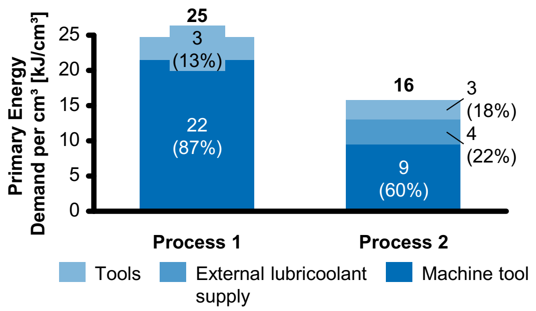


Fig. 4: Shares of primary energy demand

In this case, the electrical energy has been converted into primary energy by using a typical factor of 2.6 MJ/kWh following the German energy saving regulation (EnEV) [14]. This factor includes the German electrical energy generation mix regarding coal, natural gas, nuclear power as well as regenerative energy sources such as wind or solar energy. In this case, the influence of the tool from an primary energy point of view is around 15% of the total primary energy demand per cutting workpiece volume. Especially when using the high pressure lubricoolant supply, which leads to constant tool life or even a little increase of removed material during the tool life whilst increasing the material removal rate significantly, the influence of the tools increases. As stated previously, the external lubricoolant supply accounts for about 22% of the total primary energy demand leading to saving potentials when a reduction of pressure and volume flow is possible.

4. Strategies and possibilities of optimized utilization

High pressure jet assisted lubricoolant supply needs to be adapted to the process at hand. Higher electrical energy demands, higher costs of the necessary aggregates and special tools and tool holders require significantly higher productivity in order to be beneficial. The following qualitative Fig. 5 explains the possibilities of increased productivity due to high pressure lubricoolant supply. The drawn through lines mark the tool life while using conventional lubricoolant supply as well as high pressure supply. The slope of the constant tool life line is not derived from experiments and bases on the common findings in cutting processes, especially external longitudinal turning. The dashed lines mark constant main times. It is obvious that using the high pressure supply leads to higher material removal rates and thus to shorter main times. As stated previously, when using the high pressure technology, it is necessary to increase productivity significantly. In this example there are basically two possibilities: Increase of cutting speed v_c (I) or feed f (II).

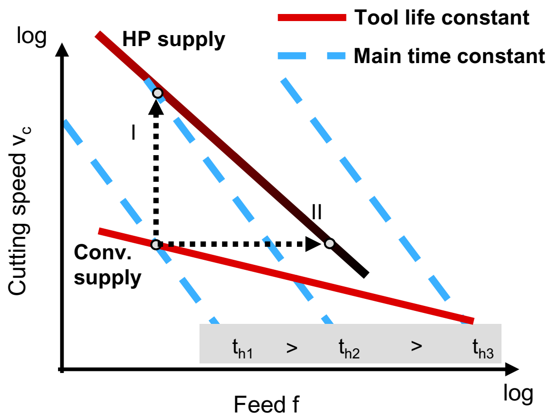


Fig. 5: Strategies for using productivity advantages of high pressure supply

In conventional cutting processes, the increase of the cutting speed leads to higher tool wear and thus decreased tool life. Raising the feed by the same relative amount leads to less reduction of tool life in comparison to the cutting speed increase, but has the same impact on the material removal rate, consequently productivity. On the other hand, the increase of the feed intensively elevates the mechanical force on the cutting insert due to the enlarged cutting cross section. When using high pressure lubricoolant supply, mainly the temperature reduction leads to benefits of tool life. The mechanical force can not be lowered to a great extent. Therefore, the increase of the cutting speed is more advisable, since the effect of better cooling in the cutting zone enables the temperature reduction and heat transfer out of the cutting zone.

Ultimately, a productivity increase like shown in the experiments of 50% leads to an advantageous process in form of decreased electrical energy consumption and main time. Whether these reductions are sufficient to allow for the investment, can be highlighted with an example. In the following Table 2 information about working days and hours are combined with machine costs in order to calculate yearly machine costs which sum up to about 100 000 € per machine, assuming labour and machine costs of 80 € per hour.

Table 2: Simplified investment example

Parameter	Value
Work days per year	220 d
Working hours per day	8 h
Process disruptions	30 %
Work time per year	1232 h
Labor and machine costs per hour	80 €
Costs per year	**98 560 €**
Estimated high pressure supply aggregate costs	**25 000 €**

Assuming that a high pressure lubricoolant supply aggregate with filtration and tank costs about 25 000 € the productivity increase of 100 % as shown in the example before, will lead to a short amortization time below one year. Notably, this high productivity gain can only be achieved for distinct processes and workpiece materials that highly profit from higher cooling near the cutting zone.

5. Conclusion

High pressure lubricoolant supply extends the given boundaries of conventional pressures and volume flows. Thus, the choice of lubricoolant supply is one of the most important factors in machining difficult-to-cut materials such as nickel based alloys. On the other hand, the question at hand is whether higher energy consumption is acceptable regarding total process advantageousness. It is necessary to identify the required pressure and volume flow for different cutting operations.

Furthermore, it is necessary to understand the underlying working principles of high pressure jet assisted lubricoolant supply, in order to achieve higher productivities and thus assure an economically advantageous process design. As stated, the increase of cutting speeds is advisable, whereas the increase of the feed probably leads to lower process stability. Also the workpiece related properties such as heat transfer are key indicators whether high pressure is economically applicable. Especially processes with difficult to cut materials will profit from the high pressure technology, but most certainly not in every process.

In a newly started project, called “dimensioning of lubricoolant pressure and volume flow for increasing energy and resource efficiency” this task is being assessed for drilling operations. For two materials, 42CrMo4 and TiAl6V4, the influence of pressure and volume flow variations will be assessed regarding several outcomes: temperature near the cutting zone, heat transfer out of the cutting zone by the lubricoolant, tool wear development, chip evacuation from the hole as well as workpiece quality after machining. Despite the fact that 42CrMo4 is not one of the most challenging materials in cutting processes, the difference between the workpiece materials leads to a better understanding from a thermal point of view, due to significantly different heat transfer behavior. The overall goal of this project is the determination of which pressure and volume flow combination results in sufficient process stability and productivity whilst reducing the lubricoolant supply caused electrical power consumption.

Acknowledgements

The authors kindly acknowledge the funding of the project "ProHoKühl" as well as "KSS-Dim" by the Federal Ministry of Economics and Technology.

The IGF-project KSS-Dim as well as ProHoKühl of the VDW research institute initiated over the AiF is funded by the Federal Ministry of Economics and Technology according to the industrial collective research program by order of the German Federal Parliament.

Federal Ministry
of Economics
and Technology

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